Recent Advances in Ionospheric Irregularity and Scintillation Forecasting

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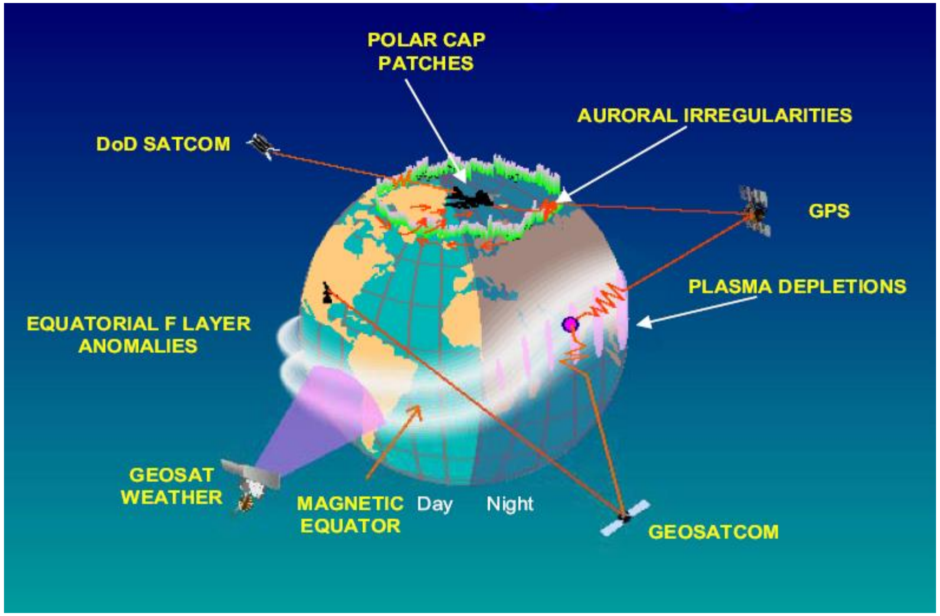
Outline



- Low Latitude Irregularities
  - Irregularity modeling
  - Scintillation forecasting
  - Contribution from C/NOFS
- High Latitude Irregularities

National Interest in Forecasting Scintillation

- Air Force C/NOFS program (Communication / Navigation Outage Forecast System) ACTD

- NOAA's Space Weather Prediction Center (SWPC) is creating the Space Weather Prediction Testbed (SWPT) ; its initial focus will be forecasting radio scintillation

- AFWA: priority #3 of a list of many topics

- AF SMC: priority #1 of a list of many topics for SSA. Scintillation and Electron density profile are KPPs for the SSAEM Mission (DMSP successor following NPOESS debacle)

- Potential AFOSR MURI program

- commercial interests for aviation (Space Environmental Tech, Inc)

Scintillation Forecasting

Existing Algorithms

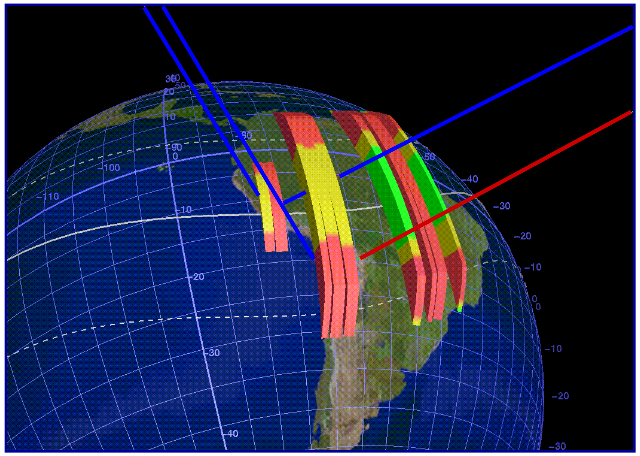
- A. Empirical Model - climatology
  - WBMOD (Secan et al.)
- B. Spatial/Temporal correlation from currently observed scintillation
  - SCINDA
- C. Empirical Parameter-based Yes/No Predictions
  - e.g., prediction based on vertical drift threshold (Anderson)

- Forecast needs not met:
  - A: Need model sensitive to ionosphere’s day-to-day variability
  - B: Need longer-term forecasts
  - C: Need model to provide spatial/temporal structure and strength of scintillation

Need first-principles model to satisfy all these needs (and establish the level of our understanding of the phenomenon)

ESF Plume Studies

- Scintillation and irregularities associated with plumes of uplifting low-density plasma
- Plume formation through nonlinear evolution of generalized Rayleigh-Taylor instability
- For radio scintillation estimates, need density around bubble/plume structures, spectra down to 100-m wavelengths
- Equatorial plasma plumes/bubbles recognized to be 3-D objects, but couldn't be treated as such at first:



(Figure courtesy of Keith Groves)

Development History – study of plumes

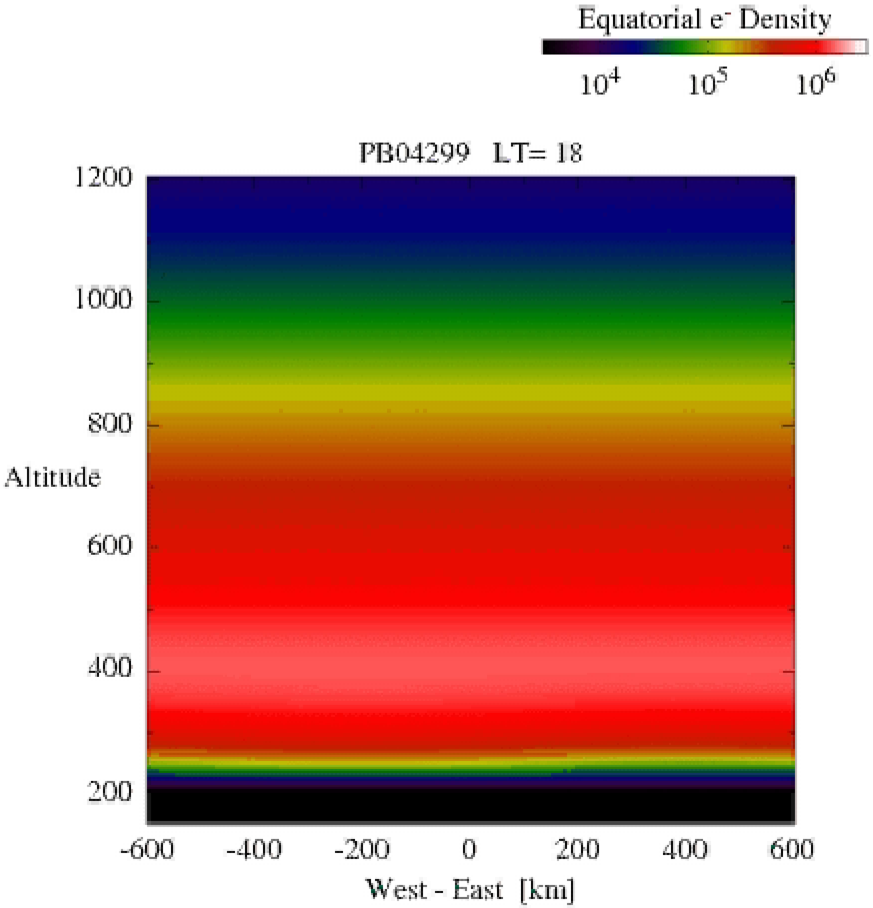
- –Solely Equatorial plane (Ossakow 1978)
- –Few Discrete layers (Zalesak et al. 1982)
- –Field-line integrated quantities (Keskinen et al.1998, Retterer 1999)
- –Full 3-D treatment (Retterer 2004; Huba et al. 2008, Aveiro and Hysell, 2010)

Plume Models

- Fluid continuity equation with production and loss
- Momentum equation
- Current continuity equation provides electric field
- Boundary conditions, coupling to ambient fields

	AFRL	Cornell	NRL
Ions	O+ (H+)	O+, NO+ (fixed proportions)	O+, H+, NO+, N2+, O2+, N+, He+
Momentum eqn treatment	Inertia-less	Inertia-less	Ion inertia
Electric potential treatment	2-D + analytic Epar	3-D	2-D
Transport algorithm	FCT	MUSCL	Donor-cell
Energy equation	Eqn of state		Energy transport eqn
Resolution (alt x lon)	5 x 5 (km)	3 x 10 (km)	10 x 5 (km)

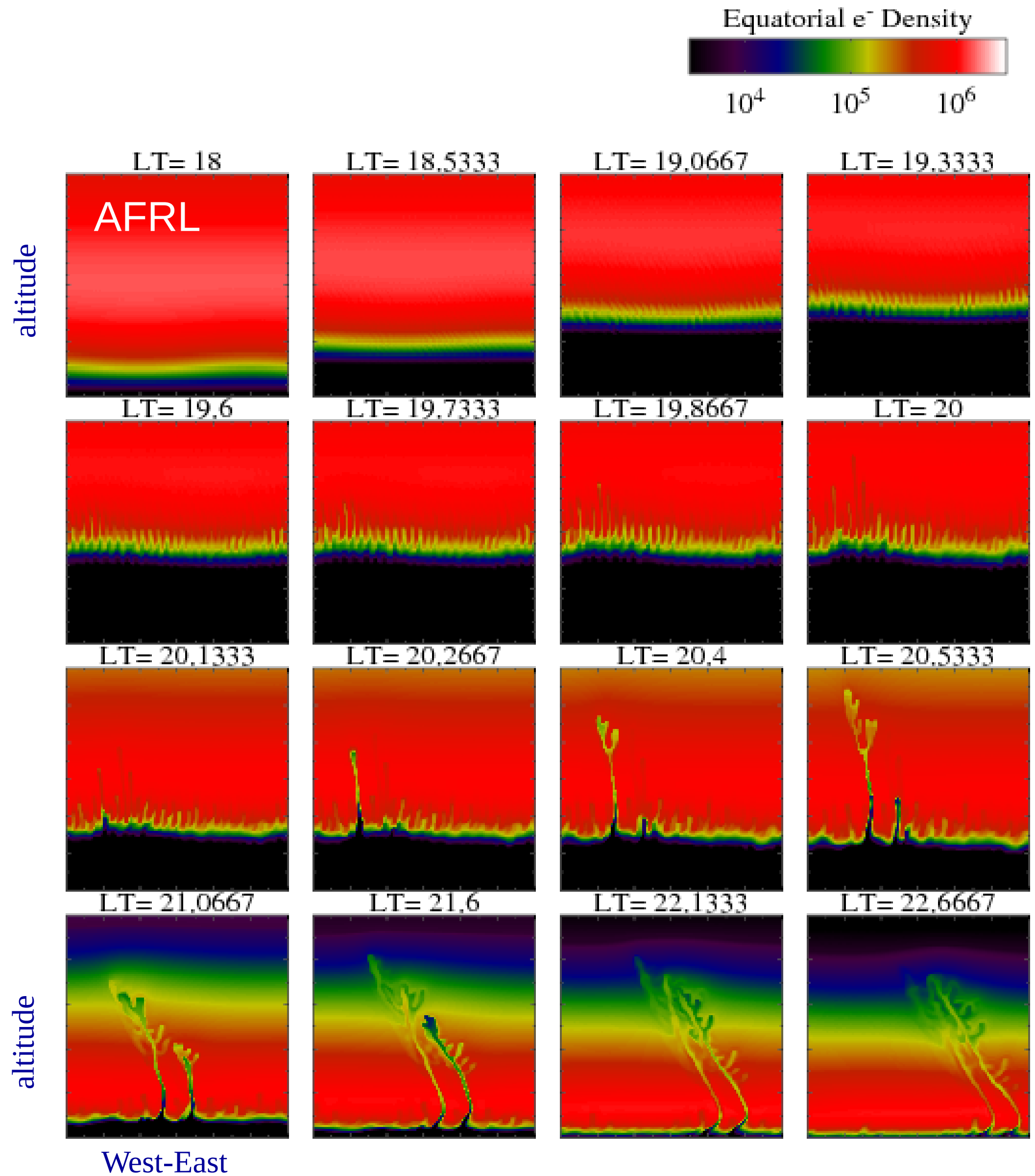
AFRL model animation



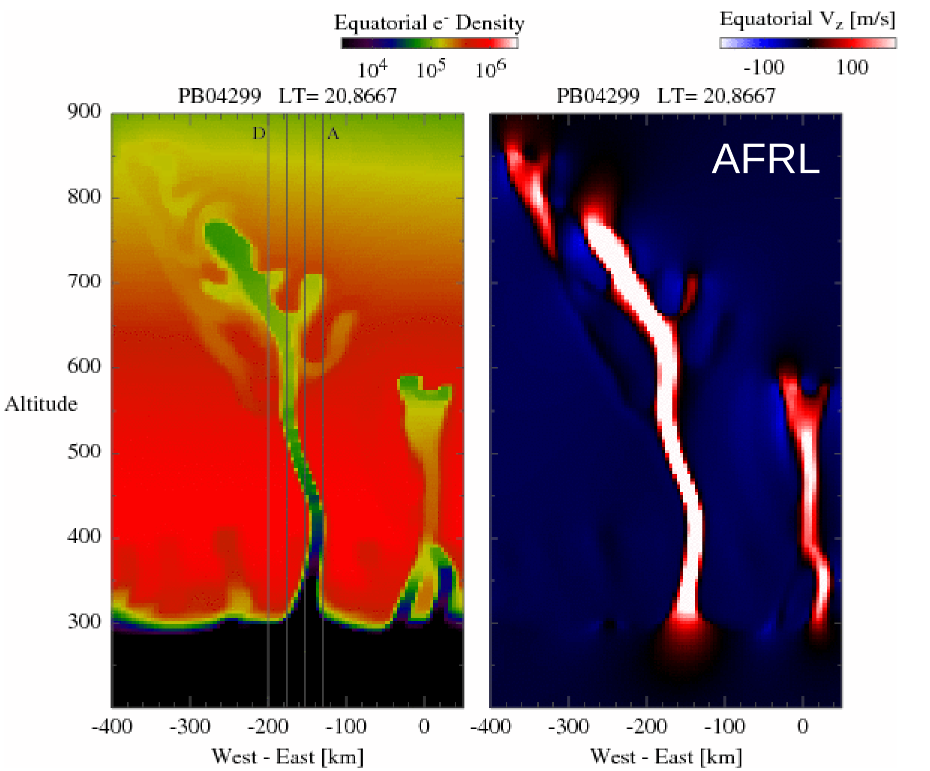
Plume Evolution

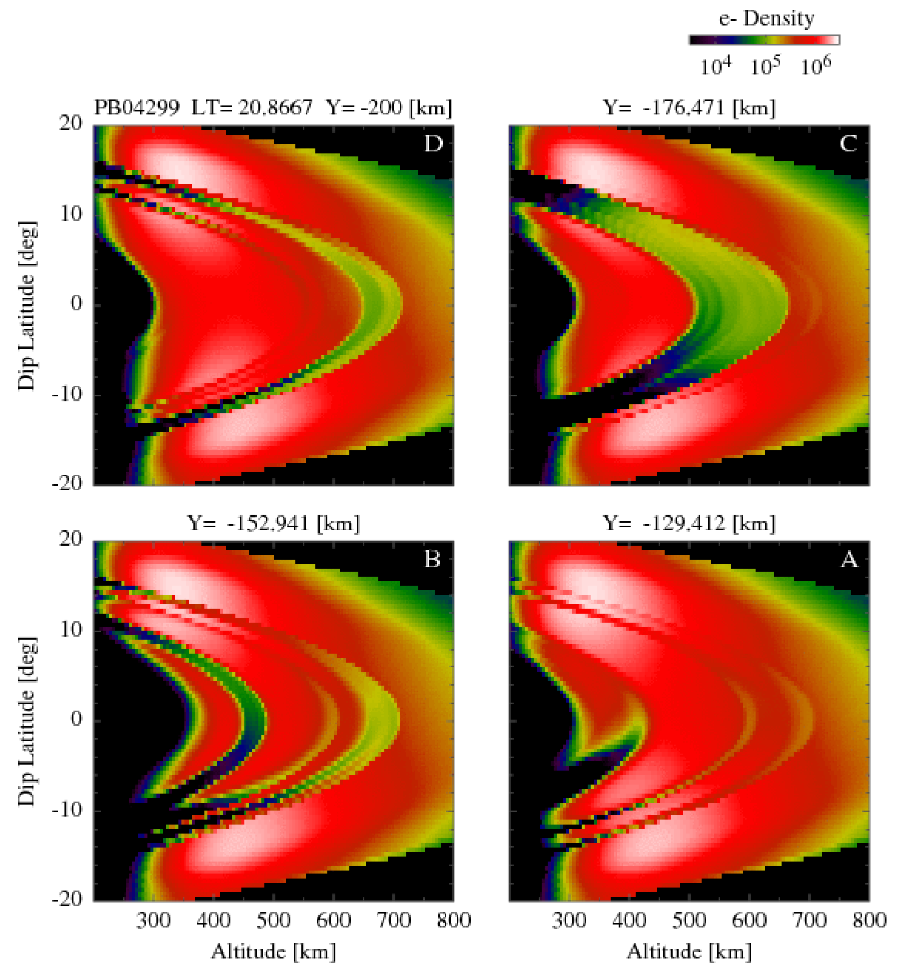
Modern 3-D plume simulations gives density structure with unprecedented detail

Evolution of plasma density in equatorial plane



3-D Plume Model

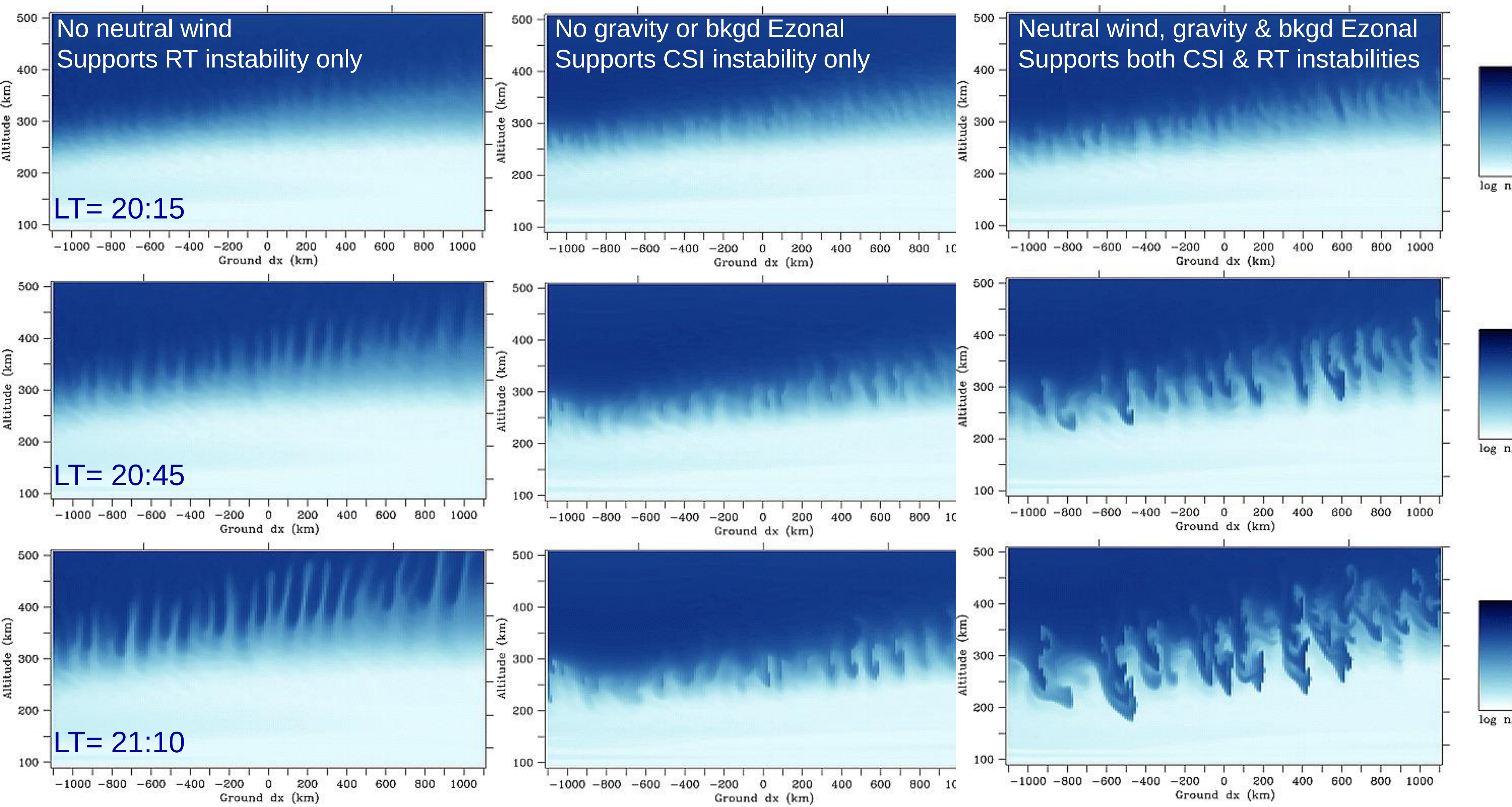




3-D structure of a plume

Altitude and longitude (above); altitude and latitude (right)

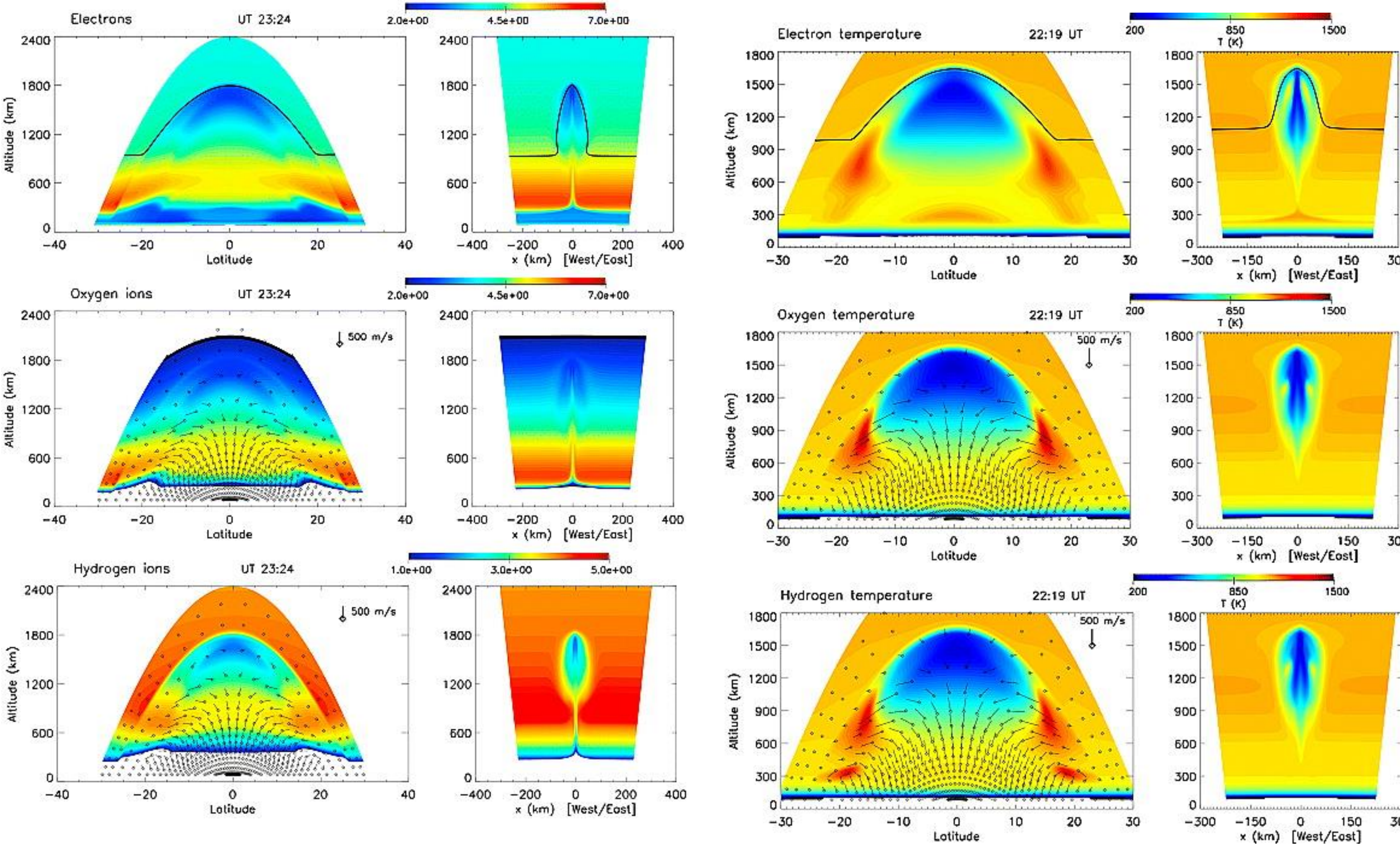
Triggering Processes



Aveiro and Hysell

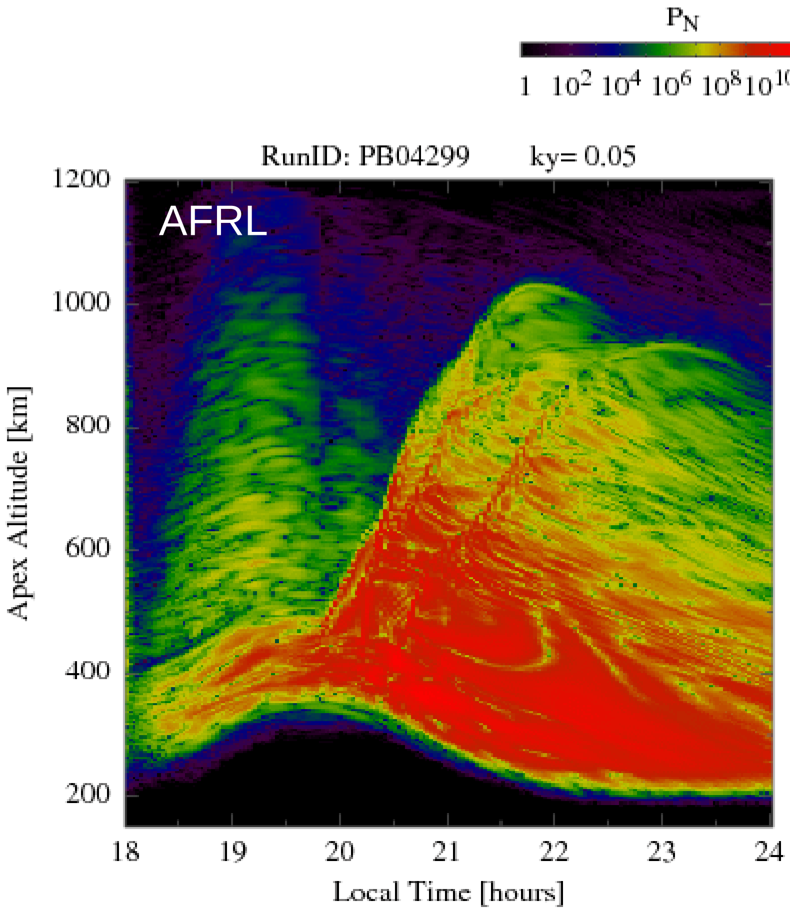
General Plume Structure

Multi-species plasma; Temp structure



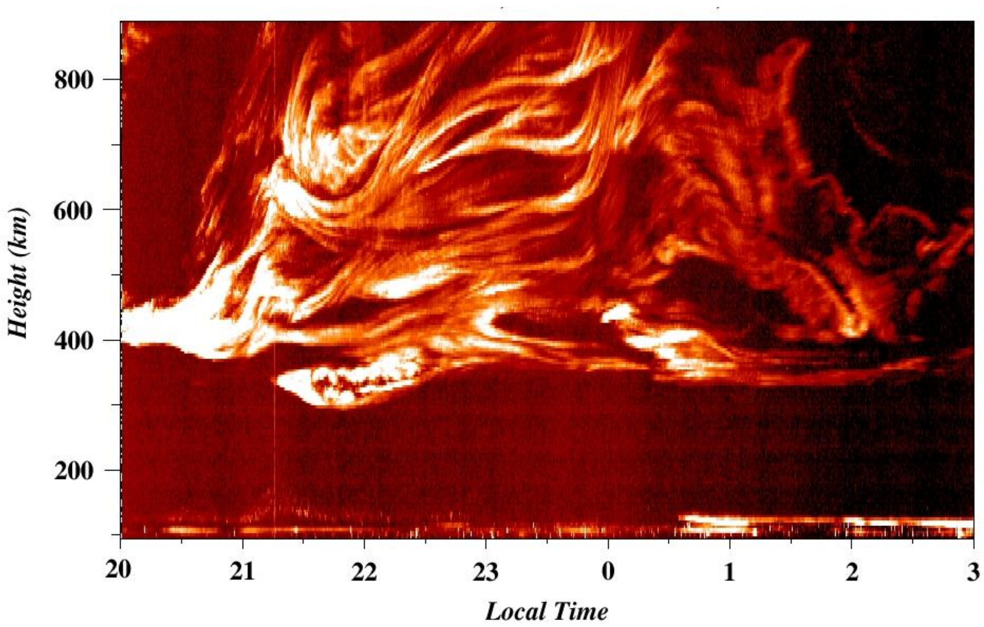
Huba et al

Spectral Component



Simulation: strength of 20-km irregularities

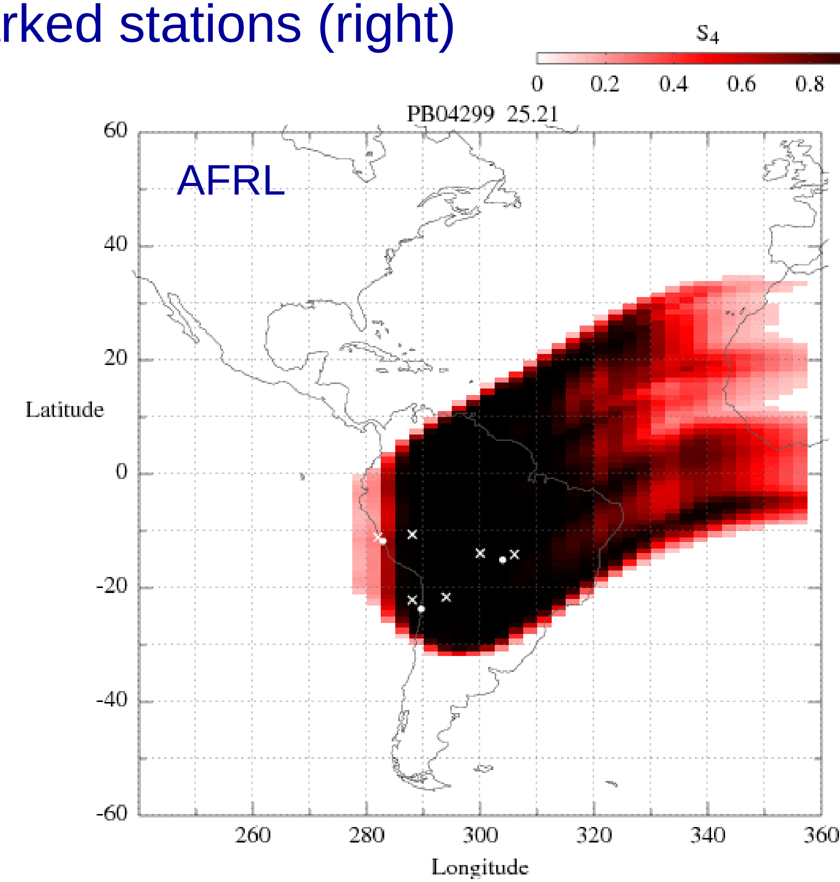
Jicamarca Radar: strength of 6-meter irregularities

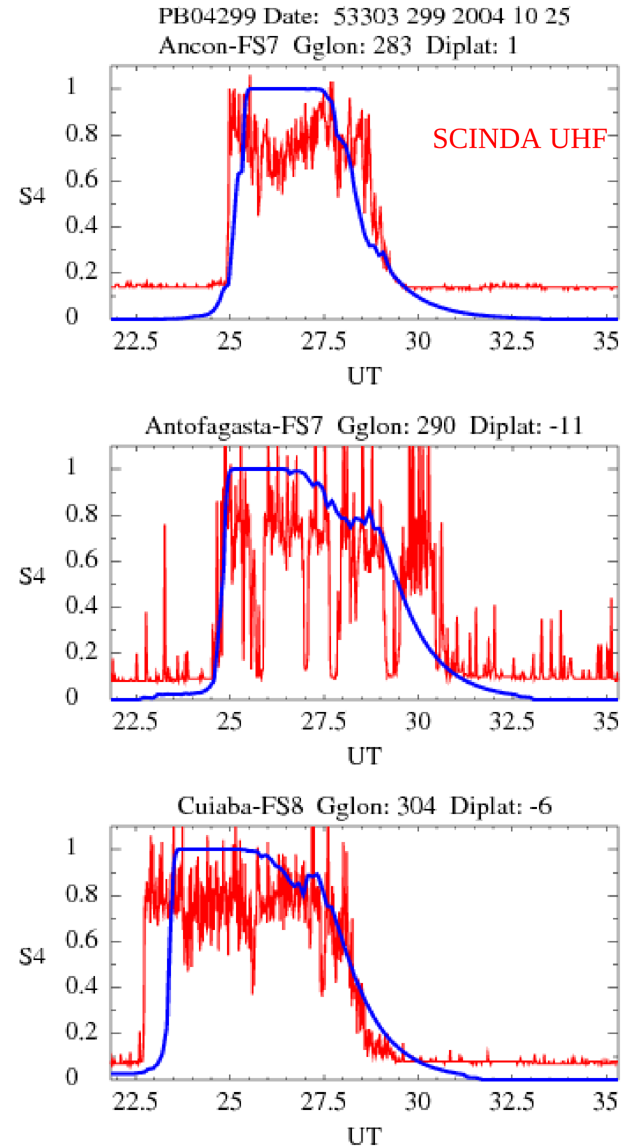


Simulations still cannot describe full range of spatial scales of natural phenomenon

Scintillation Maps

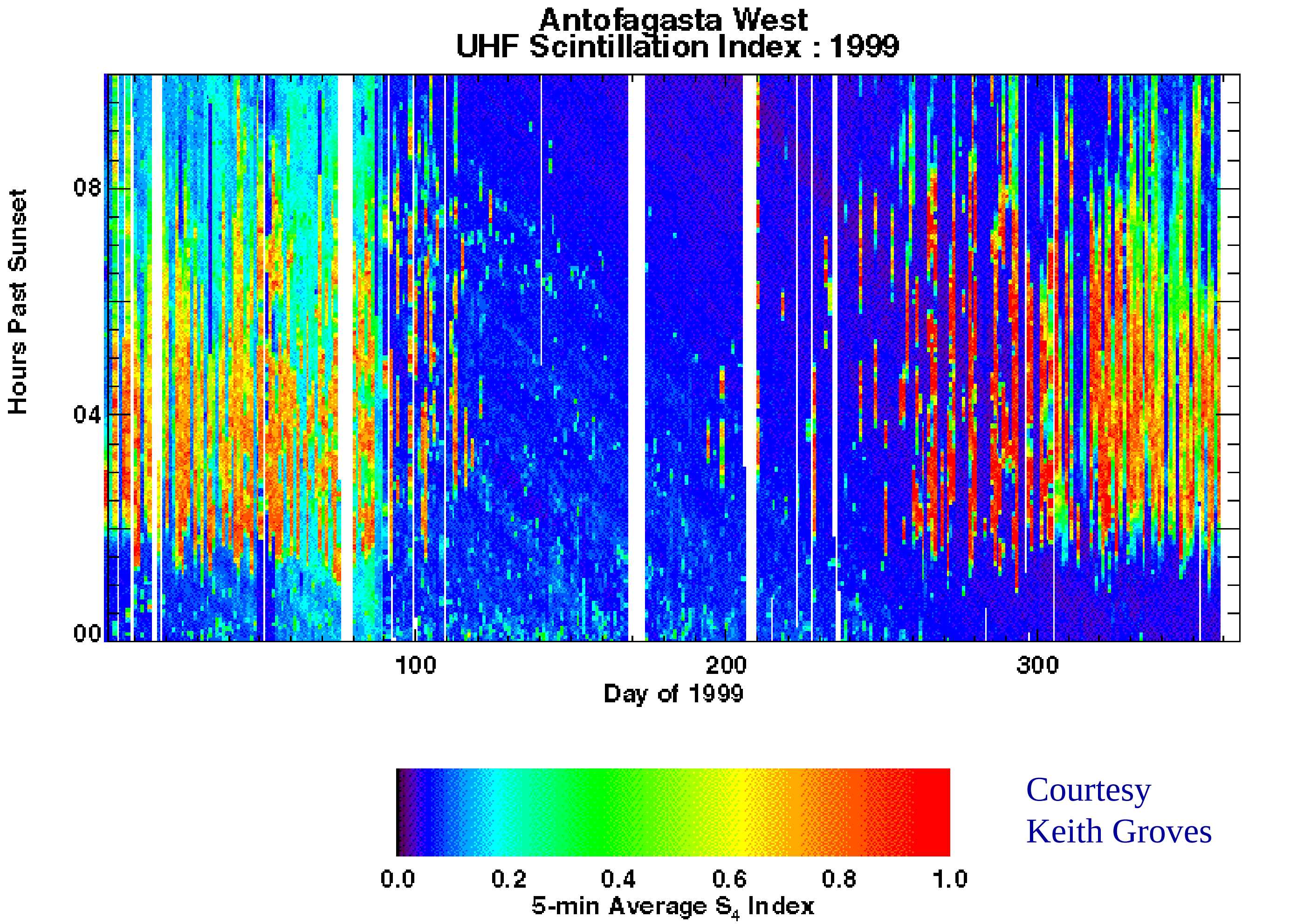
- Extrapolate model irregularity spectrum down to effective range for scintilllation, use phase-screen formula to predict S4
- Compare with SCINDA measurements at 3 marked stations (right)





SCINDA Observations

Antofagasta, Peru



Courtesy
Keith Groves

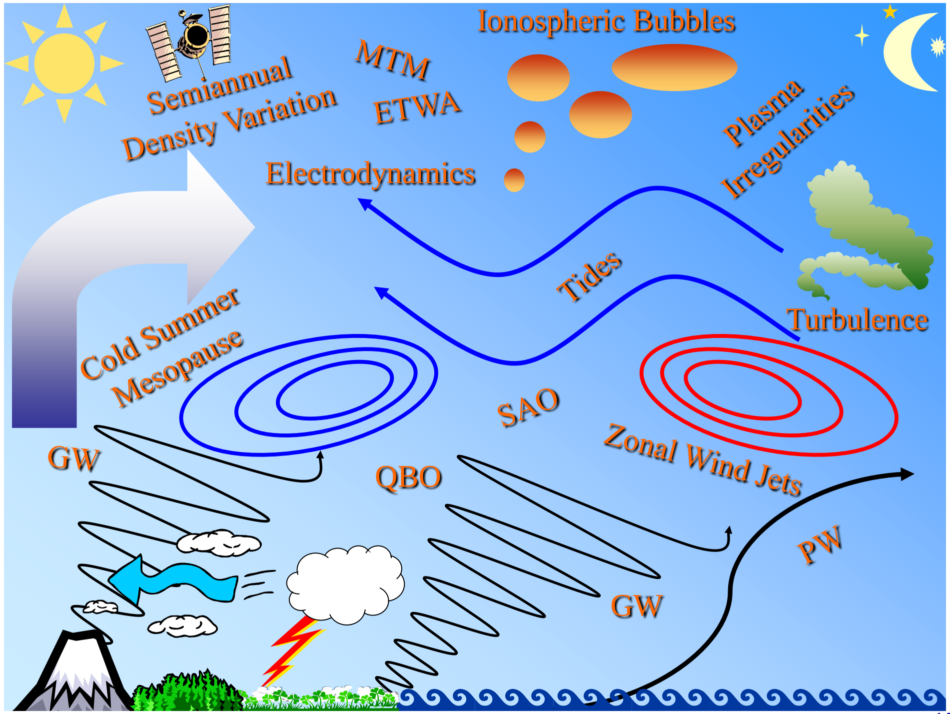
Definite seasons of occurrence, but high day-to-day variability

Causes of Scintillation Variability

- Irregularity formation sensitively dependent on ionospheric plasma drifts
- Drifts produced by dynamo action from winds
- Gradients and other inhomogeneities fuel plasma instabilities that modulate drifts

Drivers from above:
Penetration E-fields
Disturbance Dynamo

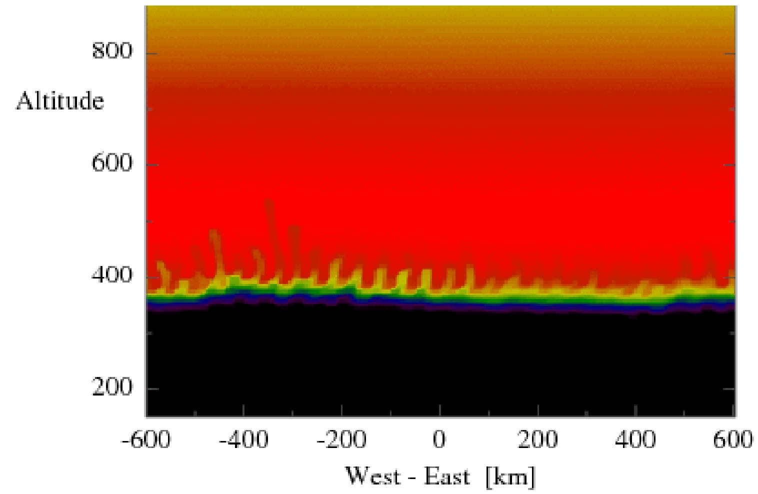
Drivers from below (Fuller-Rowell):



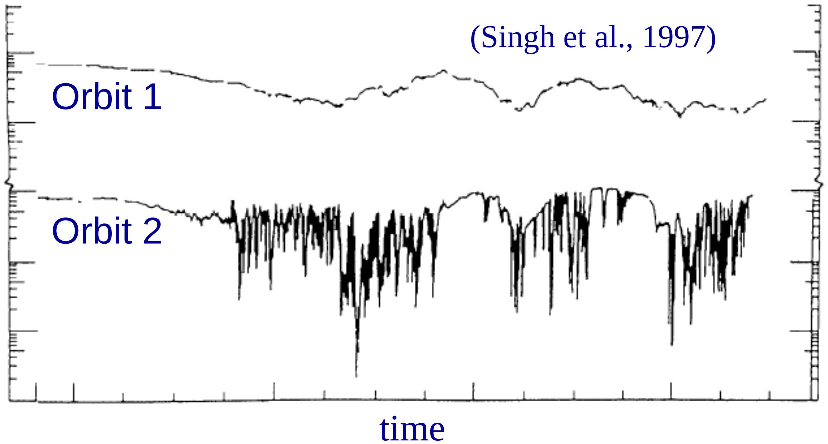
Seeding

- Not just initial density perturbation
- Mesoscale structuring of background that leads to structured enhancement of instability
- Large-scale background wave (Tsunoda)
- Examples at right: AFRL simulation (top) & AE-E observations (bottom)
- Blur distinction between variabilities of seed & strength of instability to explain day-to-day variation of irreg.

- Shorter wavelength waves <u>not</u> seeded; they spontaneously develop
- Collisional Shear Instability (CSI) (Kudeki & Hysell)
- Shorter wavelengths are an 'emergent' phenomenon (Hysell)

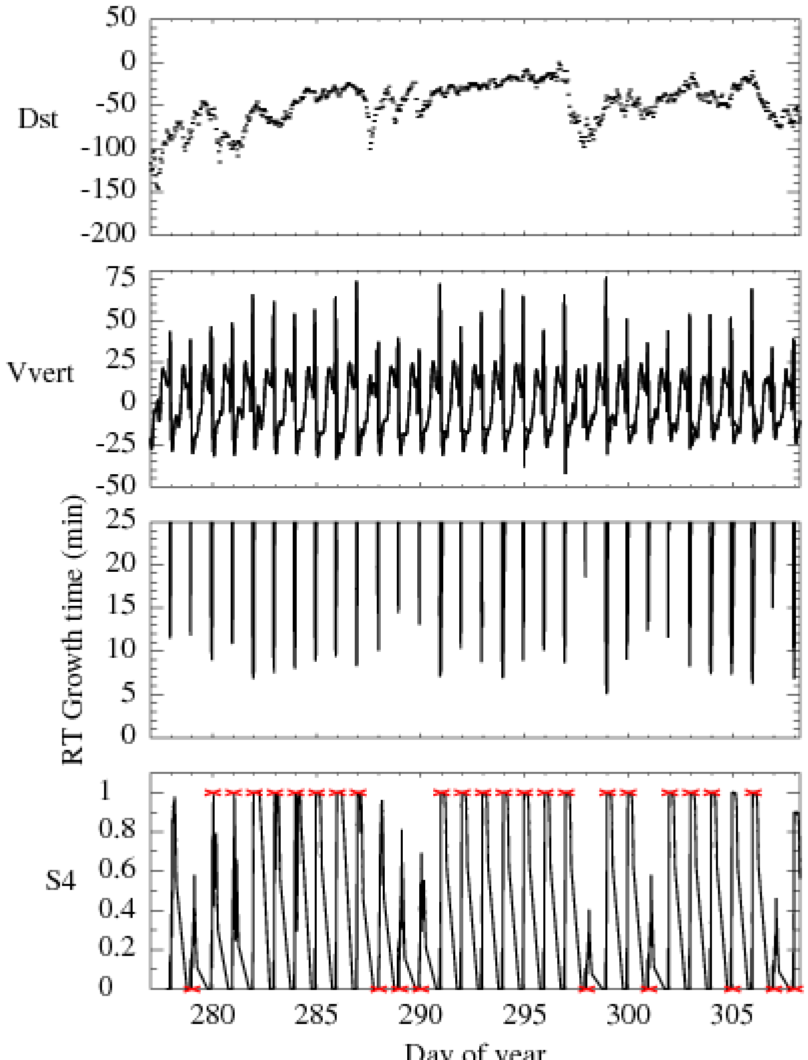


AE-E Plasma density



Prediction of Scintillation Weather

- COPEX Campaign, Brazil October 2002
- Scintillation forecast using empirical velocity model plus prereversal enhancement from ionosonde drift
- Observations: X at S4= 1 means spread-F observed
- RT growth-time threshold (T<12 min for scintillation)
- Plasma drift threshold (Vz>40 m/s for scintillation)
- Campaign occurred in active scintillation season. Variability here is discriminating days on which spread-F will not occur. This, we see, is due to geomagnetic activity

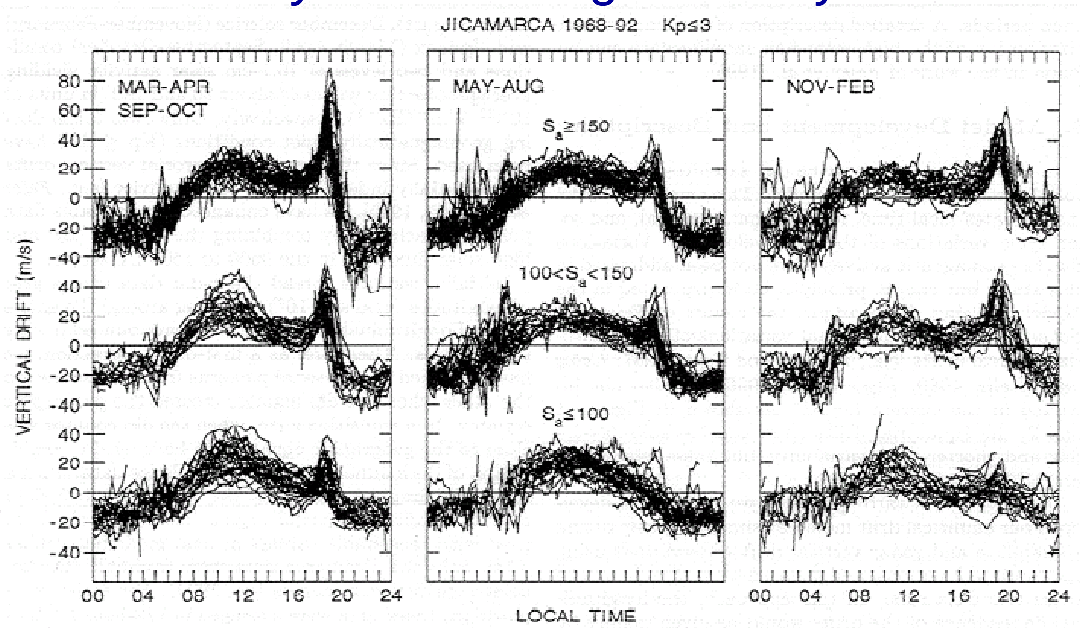


Retterer and McNamara AGU 2005

Difficulty: The Uncertainty in Ambient Forecasts

Scintillation sensitively dependent on ambient conditions in ionosphere
Ambient conditions are hard to forecast:

- Dependent on highly variable external drivers
- Highly variable themselves
- Difficult to remotely sense in a global way



Variability in Plasma Velocity (Scherliess and Fejer 1999)

Until we have a whole atmosphere model driven appropriately at high latitudes and low altitudes to predict the ionospheric drifts, direct measurements of plasma drifts in-situ delivered in real time is our only hope for scintillation forecasting

C/NOFS - Mission
Satellite: Instruments

Electric Field Instrument

Vector Electric Field Instrument (VEFI)

- Developed by NASA/GSFC (R. Pfaff PI)
- Measures: Vector AC and DC electric fields

GPS Receiver

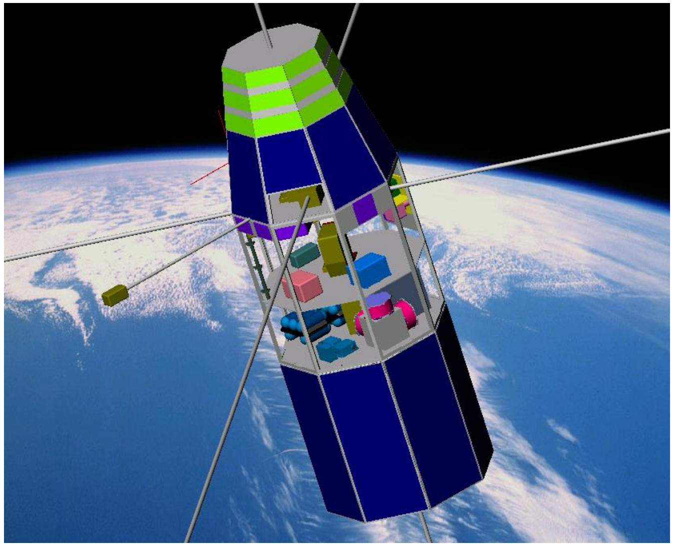
C/NOFS Occultation Receiver for Ionospheric Sensing and Specification (CORISS)

- Developed by Aerospace (P. Straus PI)
- Measures: Remote sensing of LOS TEC

RF Beacon

Coherent EM Radio Tomography (CERTO)

- Developed by NRL (P. Bernhardt PI)
- Measures: Remote sensing of RF scintillations and LOS TEC



Orbit

13^{o} inclination

400-700 km altitude

Launch: April 2008

Plasma Sensors

Planar Langmuir Probe (PLP)

- Developed by AFRL/VS (D. Hunton PI)
- Measures: Ion Density, Ion Density Variations, Electron Temperature

Ion Velocity Meter (IVM)

- Developed by Univ. of Texas (R. Heelis PI)
- Measures: Vector Ion Velocity, Ion Density, Ion Temperature

Neutral Wind Meter (NWM)

- Developed by Univ. of Texas (R. Heelis PI)
- Measures: Vector Neutral Wind Velocity

C/NOFS Results (to date)

1. Extreme coldness of ionosphere and thermosphere

   Ionization composition changed: topside scale height is small, O+/H+ transition altitude is low (Result of extreme solar minimum)

2. Post-midnight irregularities

   Large plasma irregularities seen in spite of low solar activity, but at a different local time than anticipated: Irregularities not seen after sunset (no PRE) – instead, seen after midnight

3. Dawn depletions

   Large-scale density depletions are seen at dawn (Seen by DMSP satellites as well)

4. Plasma drifts for scintillation prediction

   Instrument teams still working to remove artifacts that interfere with use of measurements on an individual orbit basis. Use of drift climatology, on the other hand, is very promising

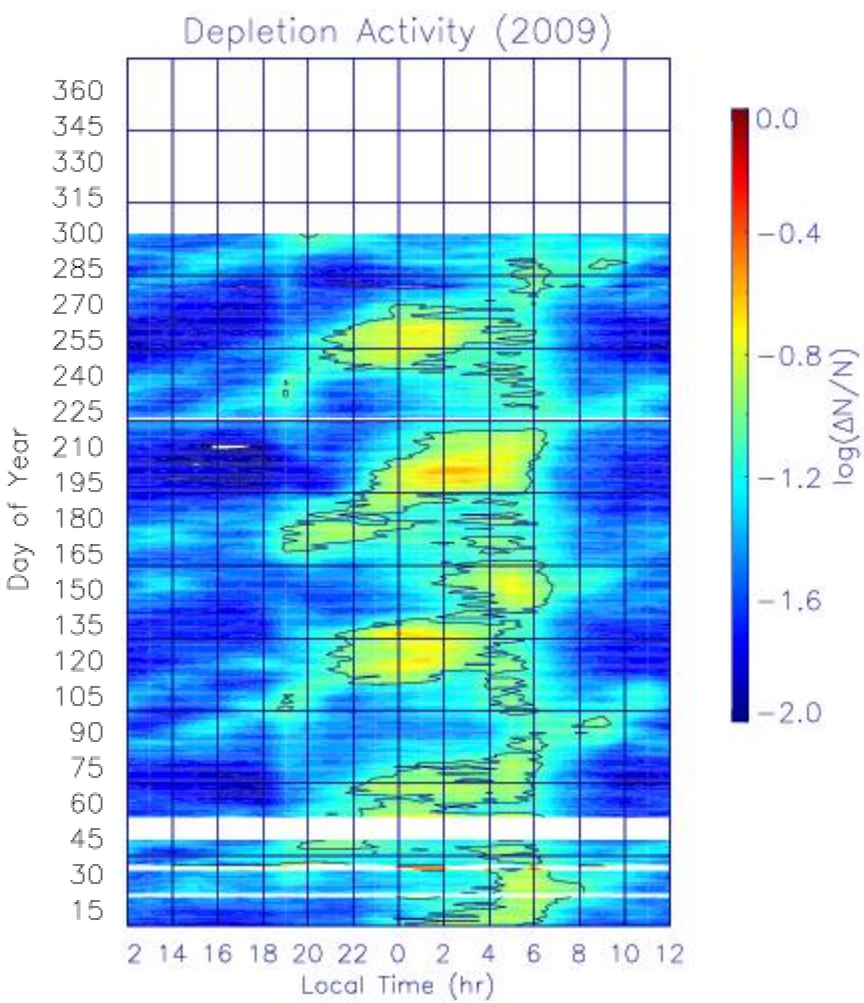
EPB occurrence in C/NOFS Era

Statistical study of PLP density depletions by Eugene Dao (Cornell)

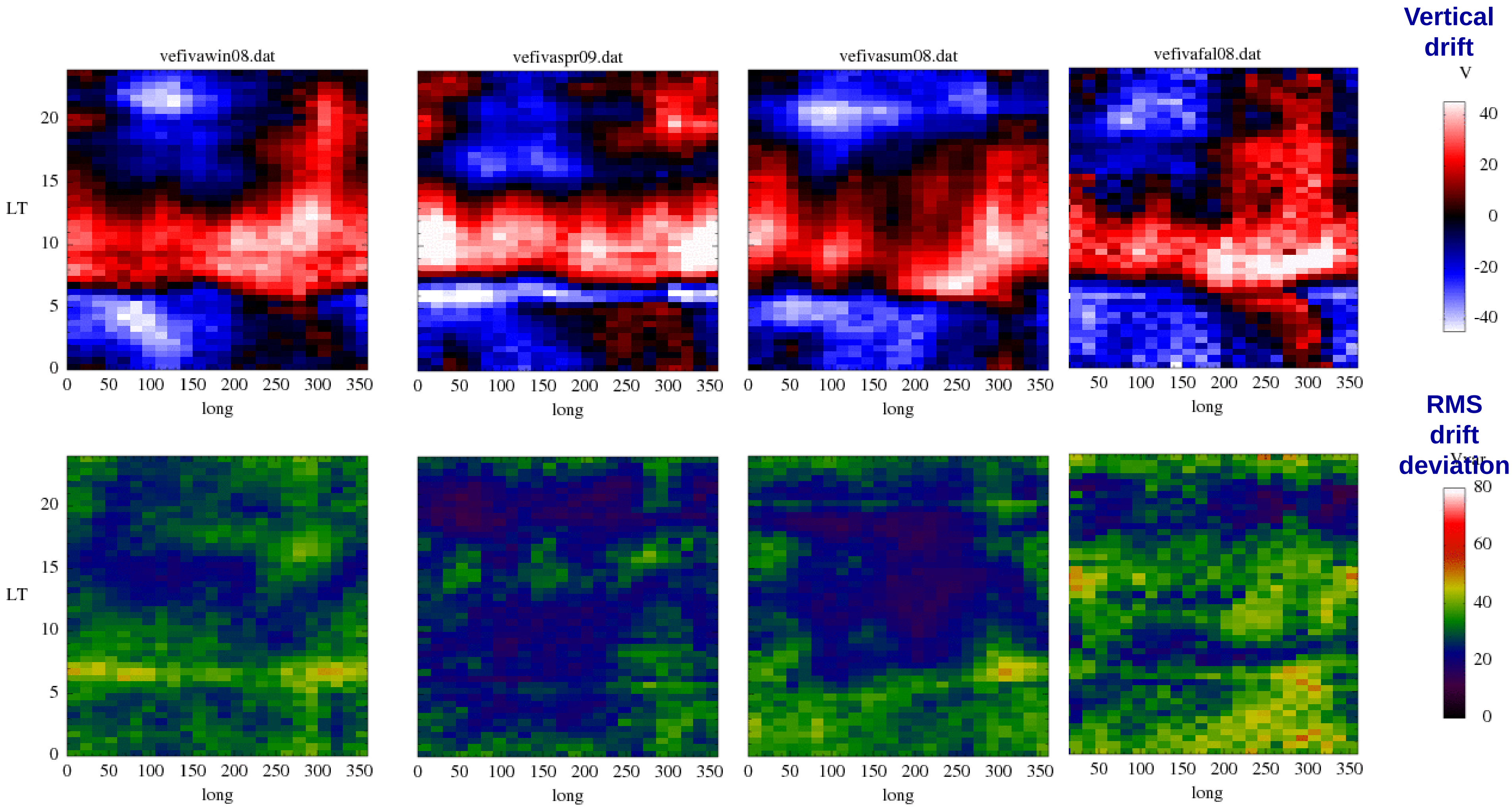
Local-time dependence of ΔN/N in 2009

Very different pattern from usual: depletions primarily found post-midnight instead of post-sunset

Climatology of equatorial plasma depletions at extreme solar min



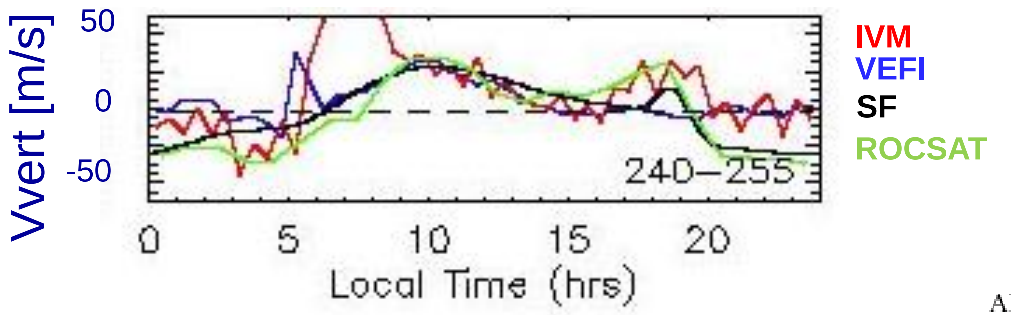
VEFI Drift Climatology

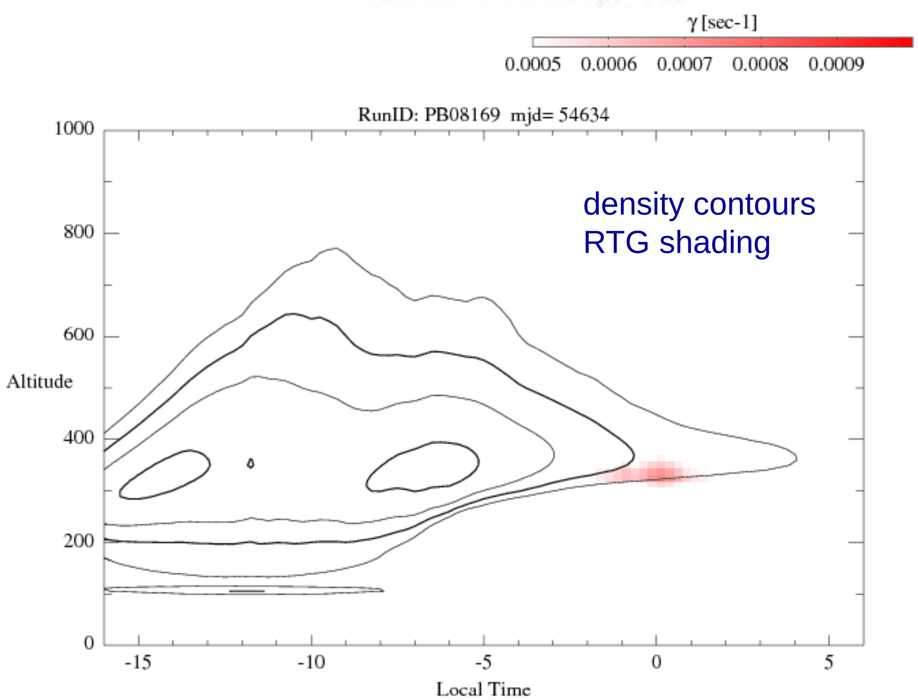


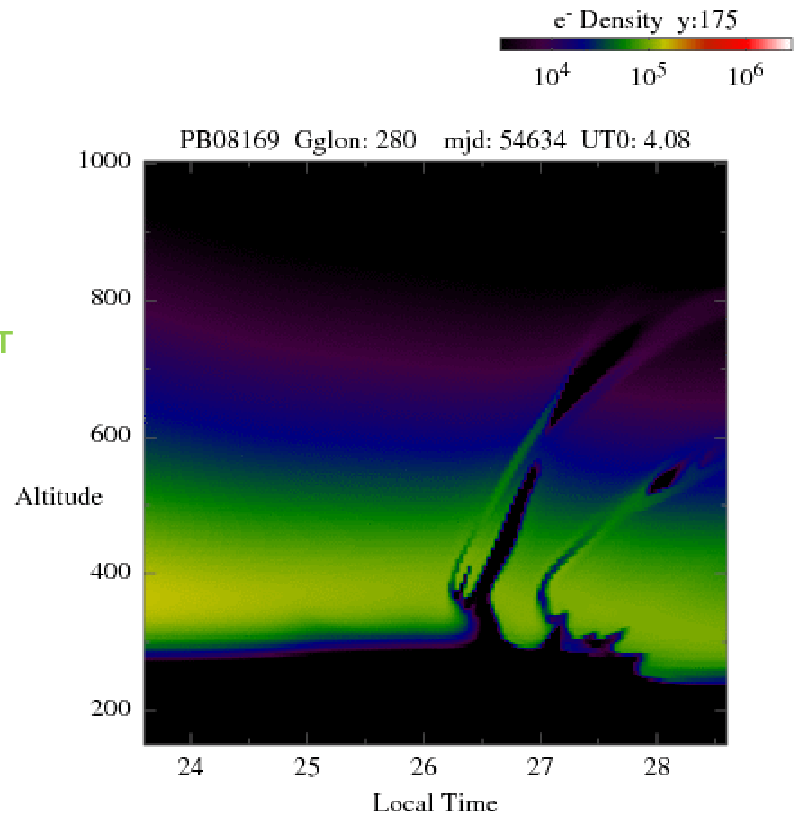
Winter Spring Summer Fall

Origin of Post-Midnight Irregularities

No nocturnal downward drift at certain seasons and longitudes







Simulated density structure in equatorial plane as plumes pass overhead, from 3-d plume model

DMSP Equatorial Bubble Occurrence

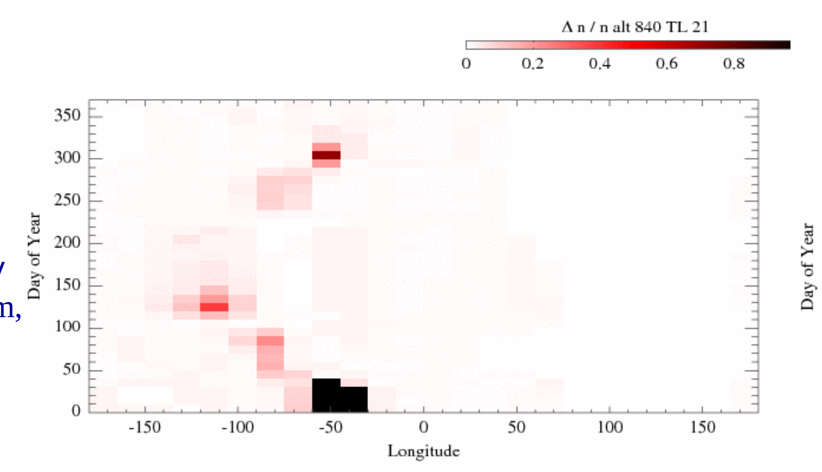
Evening Sector

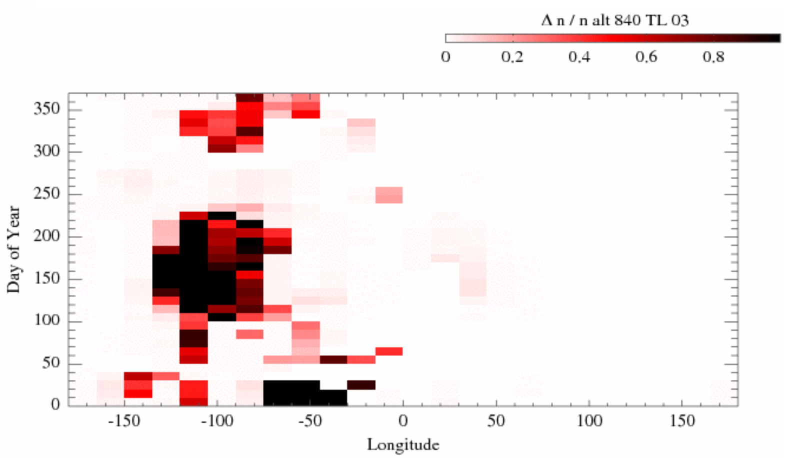
Dawn Sector

PBMOD

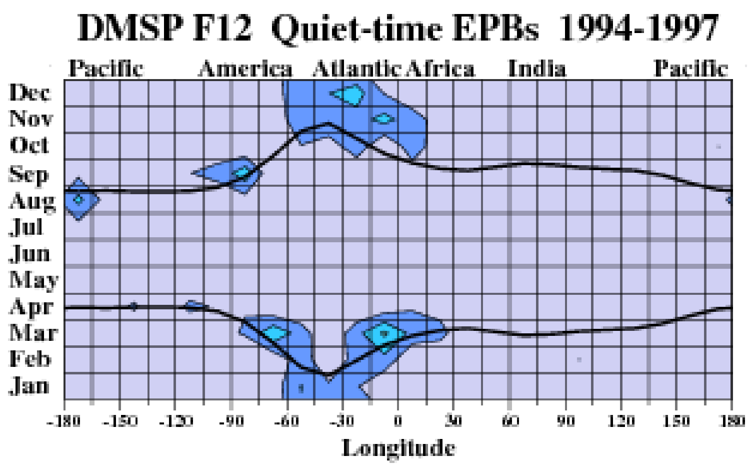
Using C/NOFS drift Climatology, density perturbation at 840 km,

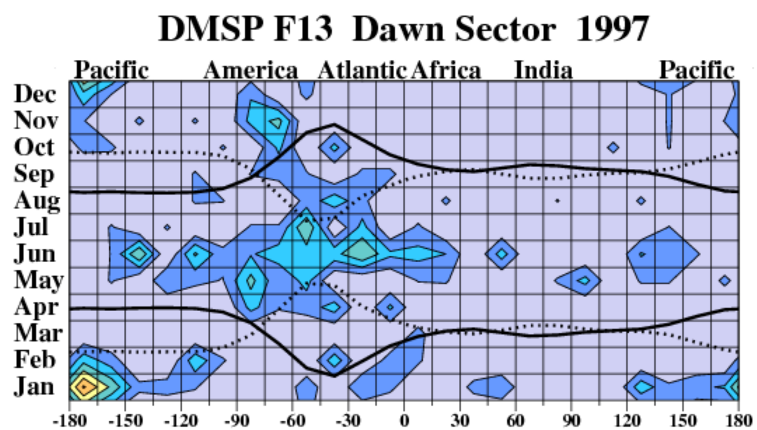
$\Delta n / n$





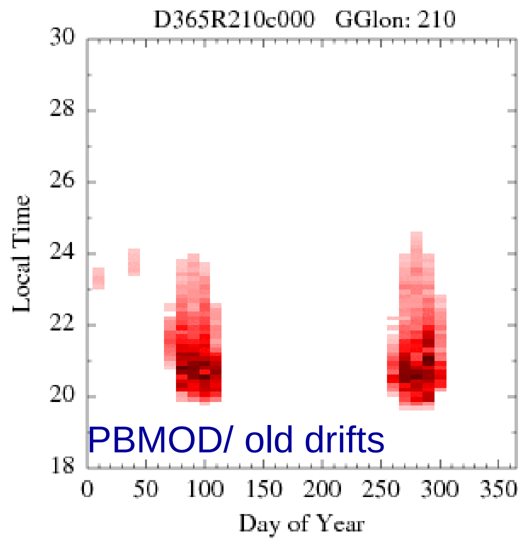
DMSP

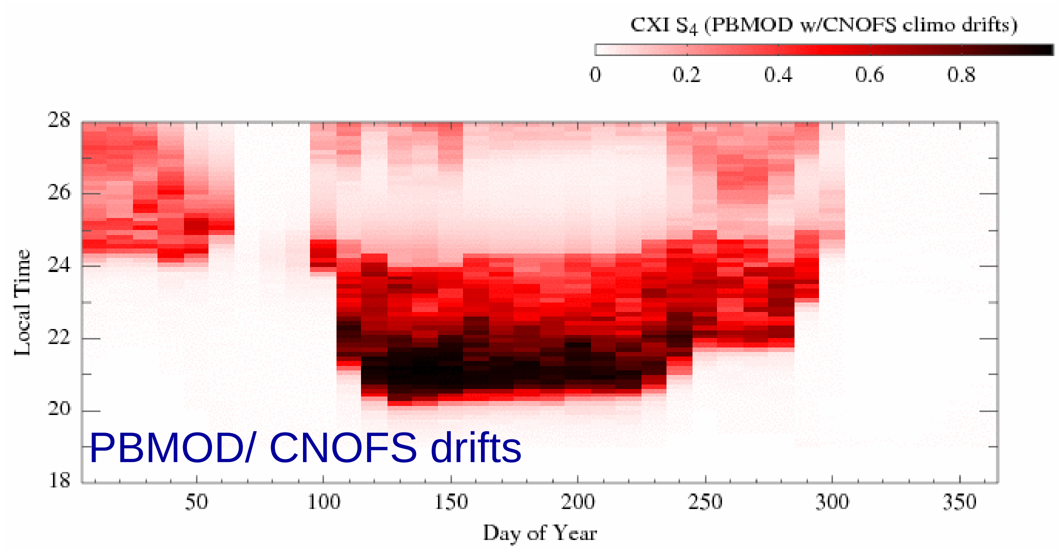


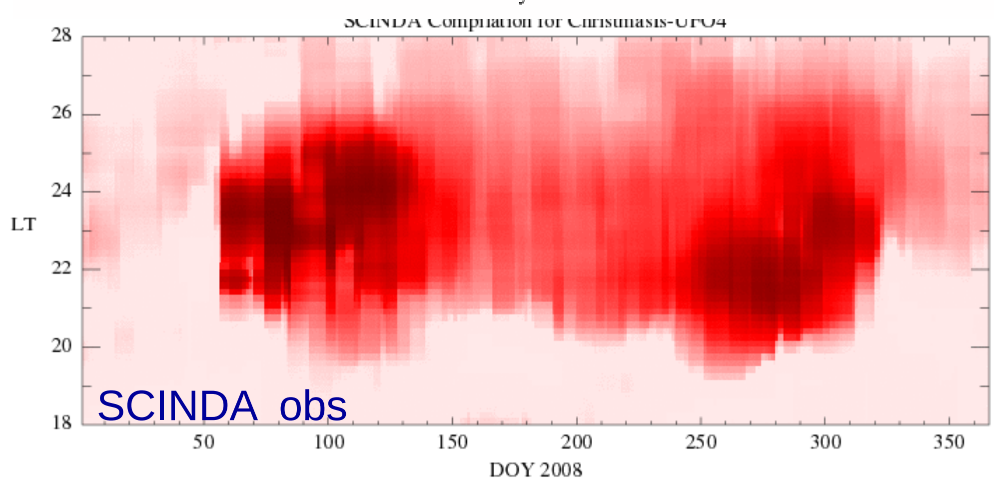


Scintillation at Solar Min

Christmas Island

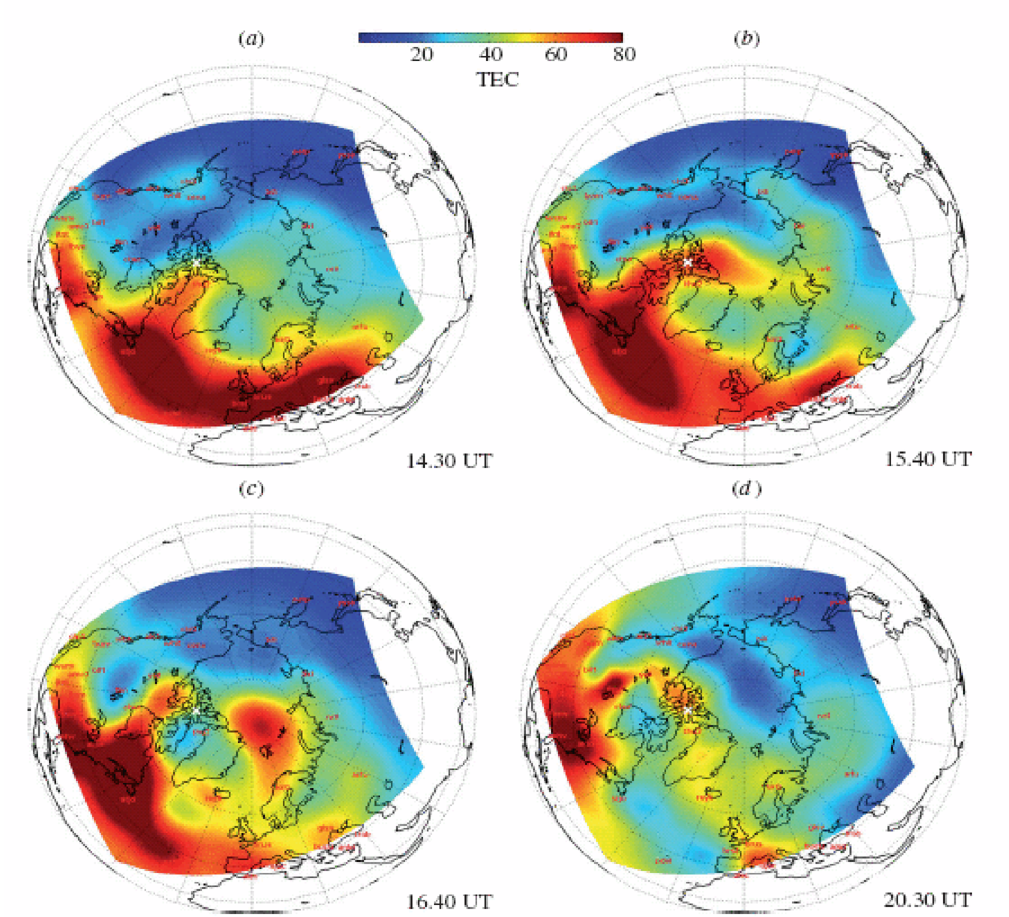






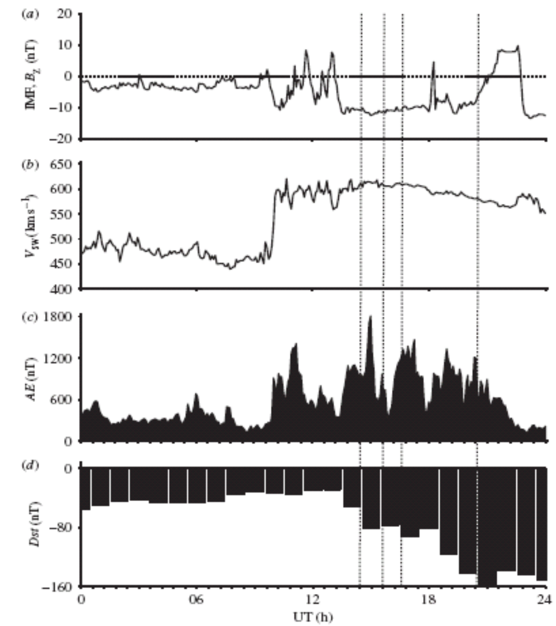
UHF Scintillation S4 parameter at Christmas Island 2009

High-Latitude Irregularities



Patch Formation on 6 Nov 2000
Tomographic reconstruction of TEC

Pokhotelov et al. Proc Roy Soc A (2010)



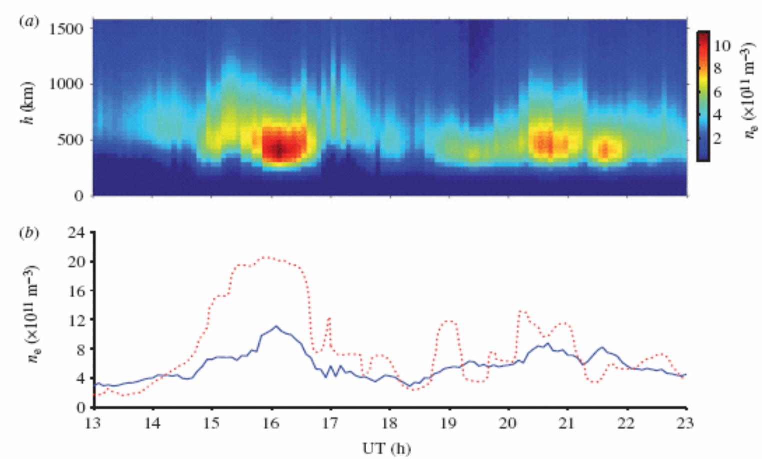
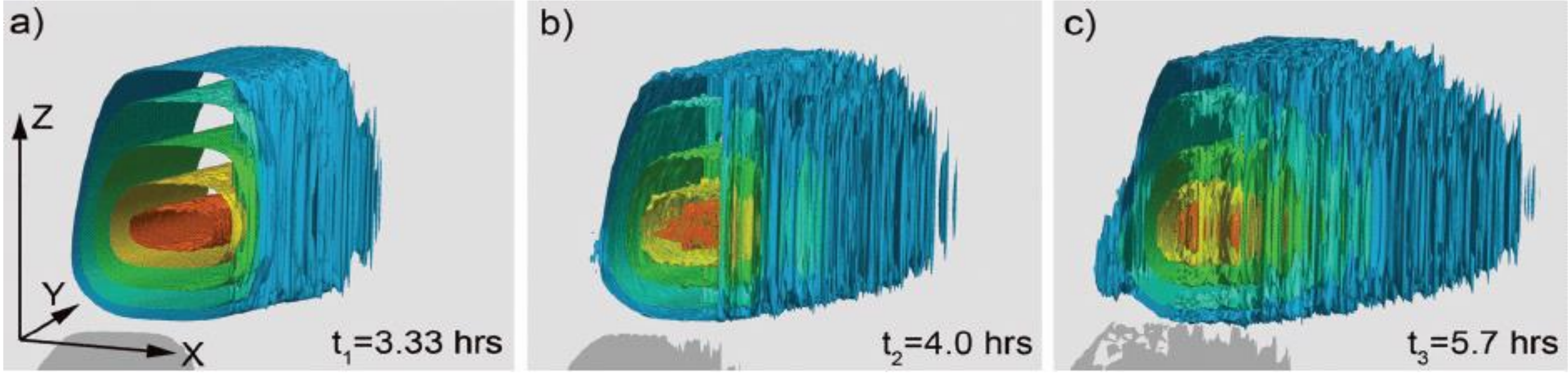


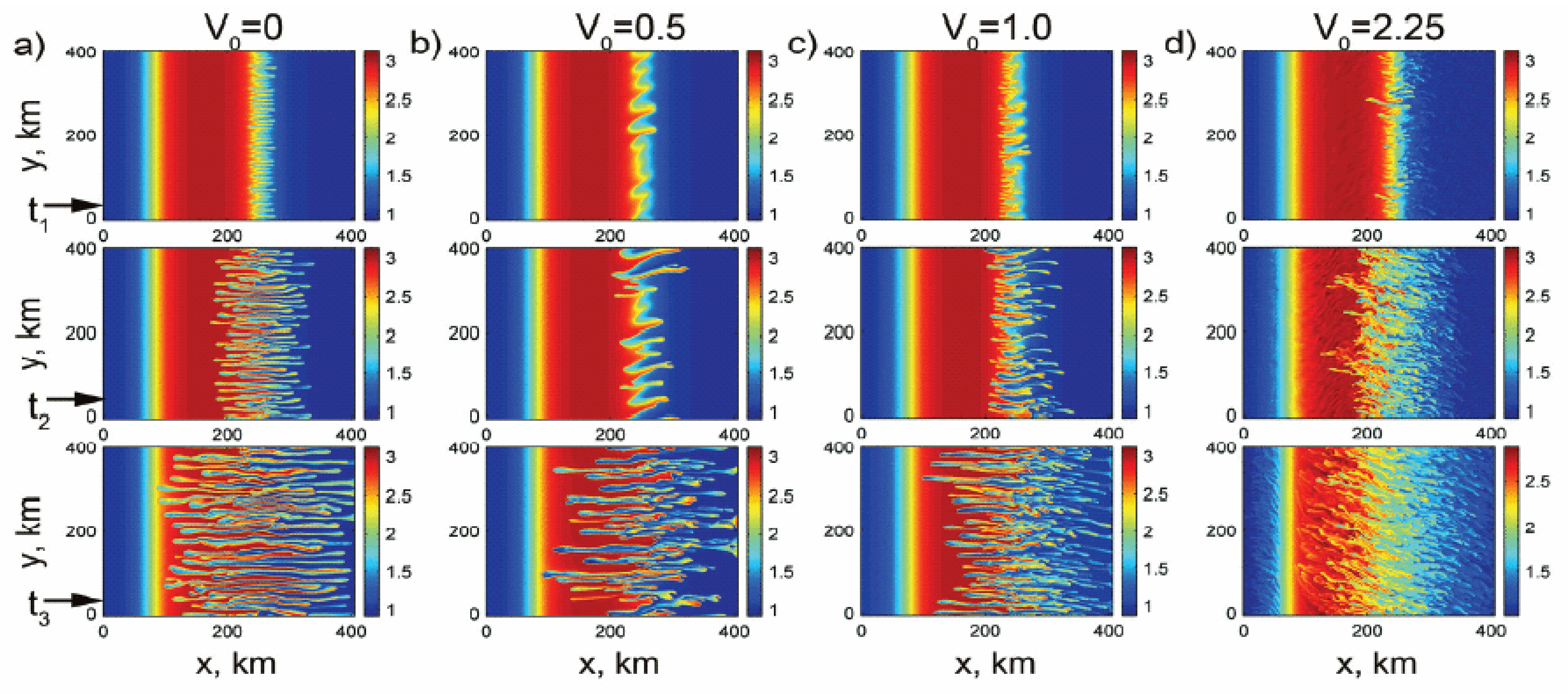
Figure 9. (a) Shows a tomographic density reconstruction over the Resolute station during 6 November 2000. (b) Shows F peak density obtained from the CADI ionosonde data (red line) and from the tomographic reconstruction (blue line).

High-Latitude Irregularities



3-D fluid simulation of irregularity development on plasma patch (third dimension is parallel to B (z direction); other contributions to conductivity along field line tend to stabilize gradient-drift instability)
-- Gondarenko and Guzdar, JGR 2006

High-Latitude Irregularities



Kelvin-Helmholtz instability driver (of various strengths) combined with the Gradient-drift instability in 3-D fluid simulation of irregularity development on plasma patch

-- Gondarenko and Guzdar, JGR 2006

Summary

- Modern 3-D plume simulations gives density structure with unprecedented detail
- Low Latitudes
  - C/NOFS observations in unique solar min reveal new phenomena; C/NOFS drift climatology explains much of the observed climatology of irregularities and scintillation
  - ‘Seeding’ appreciated as more than initial density perturbation
  - Understanding of triggering mechanisms still elusive
- Low & High Latitudes: We appreciate more potential causes of day-to-day variability, but still lack the information needed to discriminate among them and predict the variability